Erosion resistance test of SiC mirror sample for ITER divertor VUV spectrometer

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RECEIVED DATE (February 5, 2024)

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KEYWORDS: ITER, VUV, First mirror, Optical diagnostics, Silicon Carbide

HIGHLIGHTS

- We studied the erosion (and deposition) effect on the SiC mirror sample caused by high-energy neutral particles for the expected environmental condition of the field mirror of ITER divertor VUV spectrometer.
- By ZEMAX software with a simplified entrance duct model, the flux of neutral particles reaching the first mirror (the field mirror) was calculated based on the particle flux reaching the first wall.
- The erosion resistance test was performed using the laboratory-scale plasma device to assess the mirror surface damage by erosion from the charge exchange neutral particles of ITER.

ABSTRACT

A series of tests have been performed to validate the resistance of the Silicon Carbide (SiC) mirror as the first mirror material of ITER VUV spectrometers to all ITER environmental conditions. In the present paper, we focused on the erosion (and deposition) of the SiC mirror sample caused by high-energy neutral particles. The flux of neutral particles reaching the first mirror was calculated using the ZEMAX software with a simplified entrance duct model. In the calculation, the particle flux reaching the first wall is necessary and the previously reported values derived from the SOLPS calculations were used. Based on this estimated particle flux, the erosion resistance tests were performed to check the erosion effect due to the high-energy neutral particles on the first mirror of ITER divertor VUV spectrometer. In the experiment, erosion was induced by exposing hydrogen and deuterium plasmas (and ions) to the SiC mirror sample. The target fluence of incident ions in experiment is based on the estimation of the flux of neutral particles in ITER. The surface shape, composition, erosion depth, and surface roughness were measured to check the damage of the mirror surface after erosion. Based on simulations and erosion resistance tests, it was concluded that the SiC mirror can be used as the first mirror of ITER divertor VUV spectrometer.

1. Introduction

While mirrors have been widely used in relay optics for spectrometers in tokamak devices, the first mirrors (or the field mirrors) in the ITER tokamak are to be exposed in harsh environmental conditions, such as baking of their attachment structure, gamma and neutron radiation, erosion by high energy particles, and deposition by impurities. In addition, they must be able to withstand various accident consequences, such as steam ingress and vibrational loads. [1-5] Silicon Carbide (SiC) was chosen as the material of the first mirror especially for ITER VUV spectrometers, because SiC can provide the good reflectivity in vacuum ultra-violet (VUV) wavelength range with the required surface roughness of ~ 2 nm as well as good resistance to the nuclear radiation and the corrosion by steam.

The primary role of ITER divertor VUV spectrometer and ITER VUV edge imaging spectrometer among three VUV systems in ITER is to identify impurity species or to obtain the information about 1-dimensional distribution of impurities in divertor and edge plasmas. [6, 7] To facilitate these measurements, these spectrometers include a set of mirrors to relay the emission lines from the plasmas to the entrance slits of the spectrometers. The first mirrors for these ITER VUV spectrometers are located inside the port plug as the front-end elements to observe the plasmas. To validate the resistance of this first mirror material SiC of ITER VUV spectrometer to all the ITER environmental conditions, a series of tests have been performed. In the present paper, we studied the erosion (and deposition) effect on the SiC mirror sample caused by high-energy neutral particles.

In the section 2 and the section 3, firstly, the conservative assessment of erosion or deposition quantity on the first mirror of the ITER divertor VUV spectrometer (ITER divertor VUV, *here-in-after*) is discussed with ZEMAX calculation results. [5] The particle fluxes on the diagnostic first wall (DFW) evaluated from EIRENE and SOLPS codes for stationary operational modes in various ITER scenarios were used as the input values of this calculation. [8, 9] In order to assess the erosion effect by the experiment method, the first mirror sample was exposed to hydrogen or deuterium ions (or atoms) in the laboratory experiment as described in the section 4. Using the erosion assessment result as the input value of the experiment, the erosion resistance test was performed to assess the mirror surface damage by erosion from the expected charge exchange neutral particles in the ITER. The test result is described in the section 5 and the conclusion is given in the section 6.

2. Calculation method of the estimated influx of neutral particles

The rate of the neutral particle flux arriving at the first mirror of ITER divertor VUV and the input neutral particle flux on the diagnostic first wall (DFW) is estimated by the ray-tracing calculation using software, ZEMAX-12. ZEMAX is the commercial software for the optical design and analysis using Monte-Carlo method for optical rays. In the present calculation, the properties of neutral particles are assumed like followings as the definitions of Ref. [5]. It is noted that nearly the same method as Ref. [5] was applied with the modifications in the last part (*seq.* #8, #9) due to more complexity of the present case.

1. Photons (rays) are considered as neutral particles.

2. Neutral particles have uniform distribution and direction in the entrance duct as the starting point of the ray-tracing. Random angular distribution of the starting particles on the DFW is used.

3. No interaction between particles is considered.

4. Following cases of the particle-wall interaction can be considered.

   - Reflection (or scattering) with the prescribed (assumed) reflectance value. The remained portion is adsorption.
   - Sputtering of the material on the reflection point (Be deposits).

5. To derive the direct normalized particle flux (normalized via staring particle flux in DFW) at the arrival position (the first mirror), the particle-wall interaction is calculated with 0 % reflectance (full absorption on the duct wall surface).

6. When the reflectance on the duct wall surface is set to be 100 % (reflectance = 1), the total (direct + indirect) normalized particle flux is derived. Reflection on the wall is assumed to be the scattered reflection with an angular distribution law following Lambertian distribution.

7. If we subtract the direct flux (# 5) from the total flux (# 6), the indirect normalized particle flux with reflectance = 1 (100 %) can be calculated as the conservative case of indirect particle flux (full reflection on duct wall).

8. As described in Ref. [5], the actual neutral particle fluxes (D + T or Be) arriving at the first mirror can be calculated by several runs of the ray-tracing for different allowance of reflection times (from 1 to ~ 6) and matrix calculation with the prescribed reflectance value (e.g. 0.5). In this paper, we found that the indirect flux portion is negligible (as shown in Figure 6) due to baffle pins in the duct (different point from Ref. [5]) and longer duct dimension when the maximum allowed reflection times is set to be 5. In addition, the matrix calculation of Ref. [5] was not performed in this paper because the derived indirect flux values are two orders of magnitude lower than the direct flux even in the case of the reflectance = 1.

9. The neutral particle flux on the first mirror can be derived by multiplying the normalized particles flux (#3 ~ #5) on the first mirror by the input particle flux on the DFW from SOLPS calculation. When this neutral particle flux is multiplied by the sputtering yield coefficient of the first mirror material, Silicon Carbide (see the table 2), we can assess the total erosion rate.

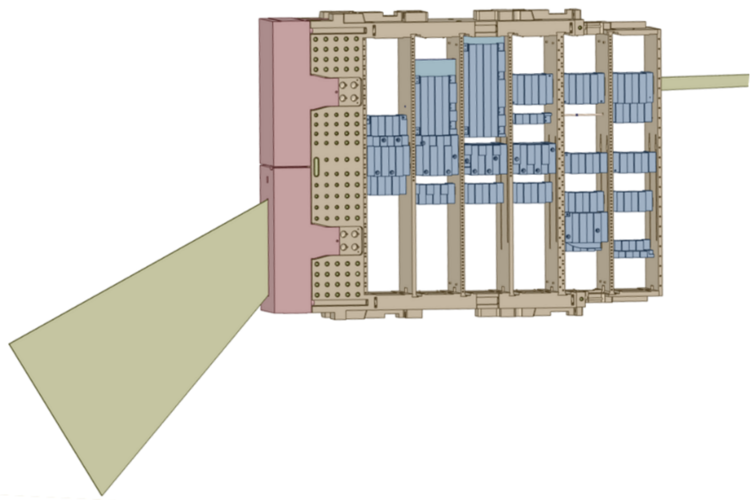


Figure 1 Detail design of DFW, DSM, the backfilling, the first mirror and the mirror box.

To estimate the neutral particle flux using ZEMAX ray-tracing calculation, the detail design of the first mirror, the mirror box, the baffled duct, the backfilling structure, DSM (Diagnostic Shield Module) and DFW were prepared to import these models into ZEMAX. However, the detailed design as seen in the figure 1 is very complicated, which increases the ZEMAX ray-tracing computation time. Therefore, a simplified design of the first mirror, the mirror box, the baffled duct, DSM slot opening, and DFW slot opening were drawn using only planes as seen in the figure 2 a), and this simple model is imported into ZEMAX model as seen in the figure 2 b) including optic lines. It is noted that the baffled duct is installed between the slot opening of DSM and the mirror box to reduce the neutral particle flux arriving at the first mirror. The minimum aperture size near focused region of beam lines on the front plate of the mirror box is 3 mm (Height) x 40 mm (Width).

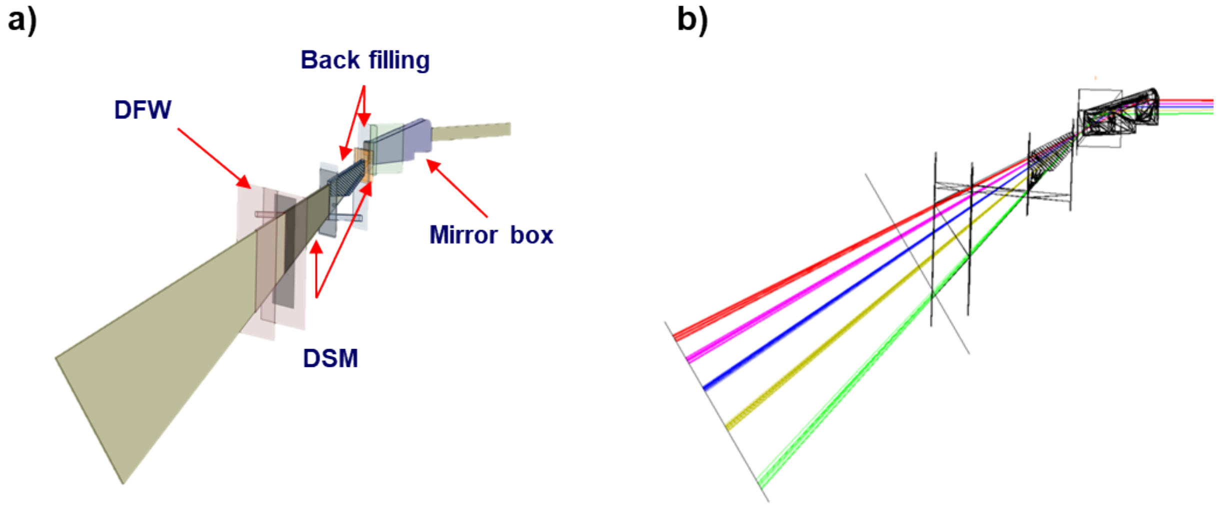


Figure 2 a) Simplified design of DFW, DSM, the backfilling, the first mirror and the mirror box, and b) imported simplified model with the optic line in ZEMAX. The dimension of slot opening in DFW is 70 cm x 3.5 cm, and the distance from the DFW to the first mirror is ~ 1.6 m.

Figure 3 a) shows the source of the neutral particles (photons) located in the entrance of duct. The initial irradiance of the source (uniform distribution in area) was set to be 1 W/cm^2. The angular distribution of rays (particles) is also uniform in all directions as Ref. [5]. The irradiation detector plane is located in the position of the first mirror surface as shown in Figure 3. Direct irradiance means that particles reach the first mirror detector directly from the source (starting points) without interacting with the wall. (#5 procedure in the previous paragraphs) Indirect irradiance means that the particles reach the first mirror detector after reflecting from the wall. (#7 procedure) The particle reflection on the duct wall is calculated as the photon scattering with an angular distribution law (Lambertian distribution). After calculation of the total irradiance (direct + indirect) with full reflection of the wall surfaces, (#6 procedure) the indirect irradiance also can be derived by subtraction of direct irradiance from total irradiance. (#7 procedure)

The direct neutral particles (irradiated photons) contribute the erosion of the first mirror mainly. The indirect neutral particles consist of two portions, the fuel (D or T) particles and the Be particles sputtered from the duct wall. Because the particle energy is to be degraded from the reflections on the duct wall, it is plausible to consider these indirect particles as the deposition source of the first mirror. The quantity of the deposition and the erosion is the function of several input parameters of the simulation such as the reflection coefficient and the erosion yield value as described in Ref. [5]. In the present paper, the erosion quantity from the direct neutral particles are assessed based on TRIM code simulation as discussed in the table 2. The deposition quantity was assessed based on the calculation results of Ref. [5], and the deposition quantity of the present study was found to be negligible as discussed in the following sections.

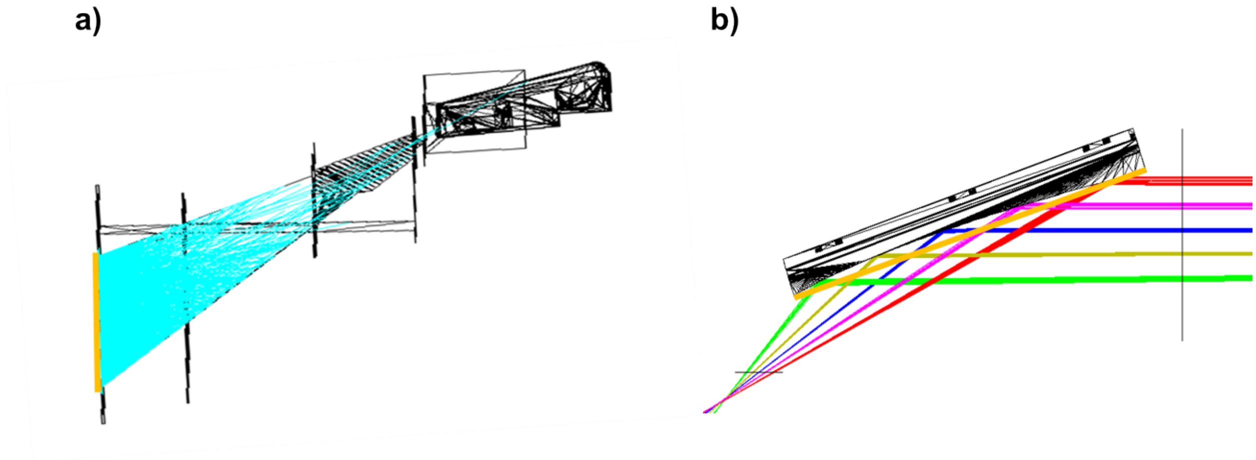


Figure 3 a) The rectangular surface source on the entrance duct of DFW, and b) the rectangular plane ray detector on the first mirror (orange color, right).

3. The estimated influx of neutral particles

3.1 Estimation of the erosion and the deposition on the first mirror of ITER divertor VUV

Normalization is carried out by setting the initial particle flux on the entrance duct = 1 W/cm^2. If we switch the unit W/cm^2 to $\#/m^2.s$ without changing numbers, the irradiance of the starting plane 1 W/cm^2 is changed to the flux 1 $\#/m^2.s$. By this change of unit, the calculated irradiance on the first mirror detector can be interpreted as the normalized particle flux for the starting flux 1 $\#/m^2.s$. Consequently, the direct normalized particle flux on the detector of the mirror (the mirror detector, *here-in-after*, figure 3) is calculated as shown in the figure 4. (#5 procedure)

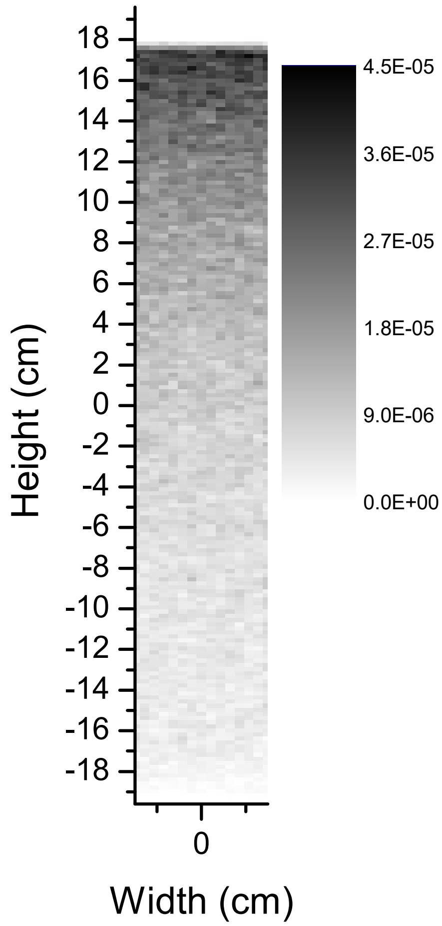


Figure 4 2-D normalized direct flux profile calculated on the first mirror detector. Unit in the right figure is $\#/m^2.s$. + direction of height is close to the plasma

The averaged 1-D normalized direct flux profile via detector height is shown in figure 5. The maximum normalized direct particle flux is 3.6×10^{-5} $\#/m^2 \cdot s$ at 17.1 cm height in the mirror detector (#5 procedure). This result shows that the front area of the first mirror (close to the plasma) is relatively more exposed to the neutral particle fluxes due to relatively larger solid angle.

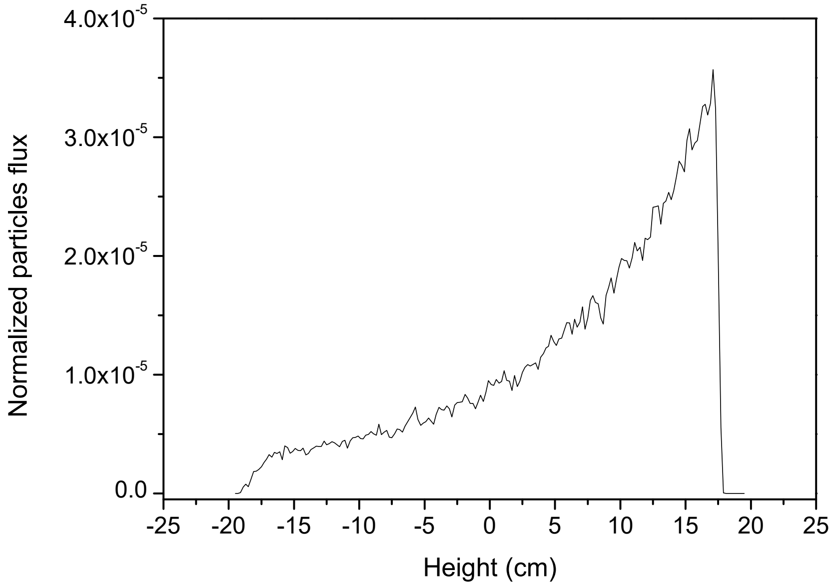


Figure 5 1-D normalized direct flux profile distribution via detector height. Unit in the left axis is #/m^2.s. (#5 procedure) Right (+) direction of x-axis is close to the plasma. Random angular power distribution was applied to the starting rays.

To estimate the indirect particle flux, we need to first run the calculation of deriving the total (direct + indirect) particle flux following the procedure #6. However due to the complexity of the model, it takes very long time to derive the total flux (direct + indirect) calculation result. For this reason, we intentionally (just for comparison study) increased the aperture size from 3 mm x 40 mm to 25 mm x 40 mm (Figure 6) for larger viewing solid angle of each detector pixel. By this test calculation, we could estimate the ratio of the indirect normalized particle flux to the direct flux. It is noted that in the current calculation, the maximum scattering times on the wall surface is set to be 5 times considering reasonable calculation times, because the energy in each wall reflection is decreased in one order of magnitude per each reflection realistically.

Figure 6 shows the calculation results for total (direct + indirect) and direct normalized fluxes from this test run. The indirect flux is resulted to be found on the edge region and the quantity of in-direct flux is calculated to be around ~ 8×10^{-7} to ~ 4×10^{-6}/m^2.s which is one or two orders of magnitude lower than the direct flux (~ 2×10^{-5} to ~ 4×10^{-4}/m^2.s).

In the calculation of Ref. [5], it was shown that the maximum erosion quantity of Mo mirror is one order of magnitude lower than the deposition quantity (table 2 of [5]), when the maximum direct flux (linked to erosion) is 3 times larger than the indirect flux (Figure 2 of [5], linked to deposition). If we consider that Mo sputtering yield is one order of magnitude lower than that of SiC (from TRIM code calculation), the erosion rate of SiC mirror is similar to the deposition rate in case of the geometry in Ref. [5]. Therefore, the result of the figure 6 (one or two orders lower indirect flux than direct flux) implies that the maximum deposition quantity (normally focused in mirror edge region) is to be ~ two order lower than the maximum erosion quantity (normally mirror center region) for SiC mirror. In other words, the erosion is dominant in the most area of the first mirror of ITER divertor VUV.

Consequently, only the erosion quantity is estimated based on various input values of particle fluxes on the first wall. The direct normalized flux of Figure 5 is considered as the total normalized flux with max. 10 % uncertainty in the following sections. The deposition rate (nm/year) can be estimated to be one or two orders lower than the erosion rate (nm/year) in the far-edge region of the mirror.

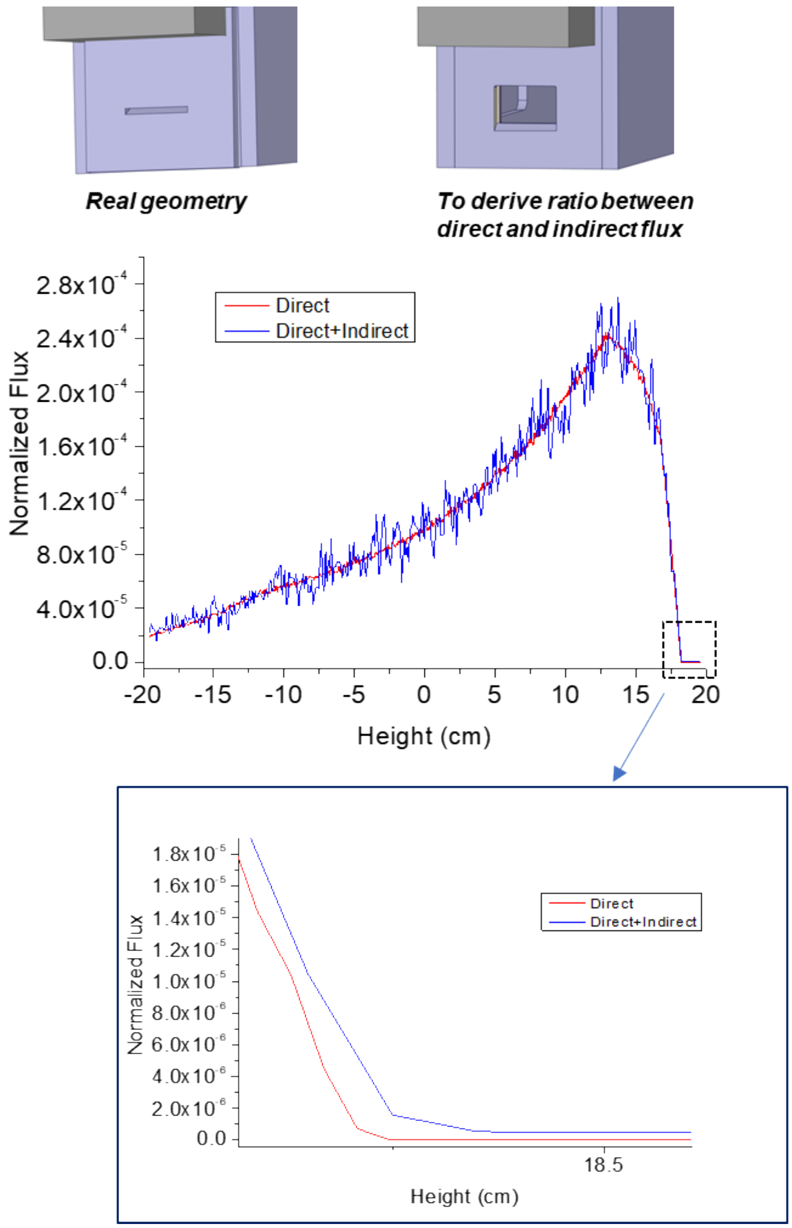


Figure 6 The comparison study with larger aperture (as a test run for larger solid angle of each detector pixel) is performed to estimate the ratio of the indirect flux to the direct flux (red). 1-D normalized total flux profile distribution with mirror detector height is shown as the blue curve. (#6 procedure) The difference of the blue curve value from the red curve value is the indirect flux quantity. In the case of this comparison study, the starting rays were set to be in cosine angular distribution function, which shows the profile result similar to Fig. 5.

3.2 The erosion estimation from Kotov's SOLPS calculation (2016)

Vladislav Kotov reported the engineering estimates of impurity fluxes on DFW of the ITER port plugs with conservative assumption in the year of 2016 [8]. The estimated neutral D and T particles flux and energy are copied in the table 1. The estimated neutral particle flux on the first wall of the equatorial port (EP, *here-in-after*) region is 9 x 10^{21} #/m^2.sec for the high plasma density (HD, *here-in-after*) case while it is 2 x 10^{21} #/m^2.sec for the low plasma density (LD, *here-in-after*) case. Based on this estimation of the neutral particle flux on the EP, the neutral particle flux reaching the first mirror is evaluated using the calculated normalized flux profile of Figure 5. Consequently, the neutral particle flux on the first mirror is derived as shown in figure 7. The maximum neutral particle flux is 3.2 x 10^{17} #/m^2·s at HD (high density case), and 7.3 x 10^{16} #/m^2·s at LD (low density case).

Neutral D and T energy and flux	UP	**EP HD**	**EP LD**
Energy [eV] (from Kotov, 2016)	100	**200**	**300**
D + T flux on DFW in ITER [#/m^2·sec] (from Kotov, 2016)	9x10^{21}	**9x10^{21}**	**2x10^{21}**

Table 1 Estimated neutral particle energy and flux on the diagnostic first wall of equatorial port (EP) or upper port (UP) for the high density (HD) plasma cases. [8]

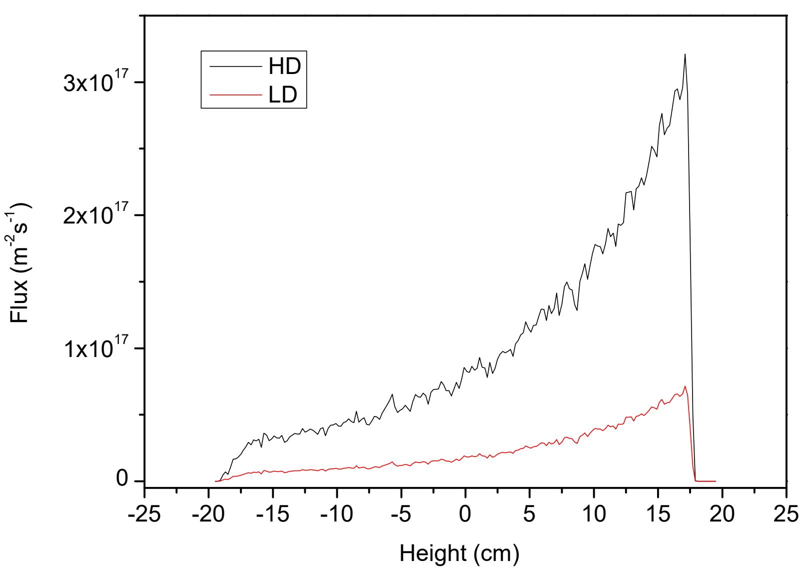


Figure 7 The calculated neutral particle flux on the first mirror based on Kotov's estimation (2016) of the input neutral particle flux. (#5 procedure)

The sputtering yields were derived and are displayed in the table 2 from the calculation by TRIM-2008 code for the input energy of 200 eV or 300 eV (also 100 eV for the reference) for hydrogen, deuterium, and tritium with the target materials of Silicon and Carbon in different injection angles of atoms. [11] Conservatively the average of four values (bold characters) of sputtering yields for 15 deg. grazing angle and 300 eV energy of D, T atoms are averaged to assess the erosion quantity in the following discussion. From this, the sputtering yield value of 0.09 for SiC is to be used in the following paragraphs. Since the total operating time of ITER plasma is 400 seconds and 30000 pulses (10 years assumed), the erosion rate of the silicon carbide first mirror of ITER divertor VUV spectrometer is calculated for this ITER experimental schedule as shown in Table 3.

Hydrogen	**100 eV**		**200 eV**	
	Si	C	Si	C
15°	0.000005	0.00002	0.0194	0.0118
20°	0.000051	0.000021	0.0204	0.0116
25°	0.000055	0.00002	0.02	0.0111
90°	0.000075	0.000045	0.0131	0.007045

Deuterium	**100 eV**		**200 eV**		**300 eV**	
	Si	C	Si	C	Si	C
15°	0.0238	0.0155	0.0614	0.0359	**0.0866**	**0.05**
20°	0.026	0.0154	0.0605	0.0343	0.0817	0.0451
25°	0.0271	0.0161	0.0567	0.0316	0.0732	0.0408
90°	0.0205	0.0115	0.0343	0.0189	0.0372	0.0206

Tritium	**200 eV**		**300 eV**	
	Si	C	Si	C
15°	0.0992	0.0591	**0.1385**	**0.0797**
20°	0.0978	0.0556	0.1282	0.0748
25°	0.0919	0.0503	0.1162	0.064
90°	0.0512	0.0288	0.0553	0.0302

Table 2 The sputtering yield of Si or C target for different energy and grazing angle of deuterium or tritium atoms. Average of bold character values, 0.09 is used as the sputtering yield of SiC in the following discussion conservatively.

	EP HD	EP LD
Max. neutral particle flux (/m^2·s)	3.2 x 10^{17}	7.3 x 10^{16}
Sputtering rate (nm/y)	365	81

Table 3 Maximum sputtering rate from the input flux of Kotov's estimation (#9 procedure). Total 10 years for 30000 pulses (400 s for each pulse) are assumed

3.3 The erosion estimation from the updated calculation of SOLPS-ITER (2021)

In the recent SOLPS-ITER simulation results database, IMAS (ITER Integrated Modelling and Analysis Suite) [9], neutral particle flux estimation on the first wall can be found. The detailed simulation results of the neutral particle fluxes to the mid plane (near DFW slot of ITER divertor VUV) are (103054/3), (103062/3), for PFPO-1 W divertor cases, and (123156/3), (123162/3) for FPO W divertor cases. It is noted that there is the additional portion of neutral particles, which is converted from the ion fluxes directly after the first collision to the wall in DFW, and this portion of neutral particles will be discussed in the following paragraphs (the tables 6 and 7). The neutral particle information shown in the table 4 is the values for the neutral particles impinging to DFW, which is resulted from the SOLPS-ITER calculation without the portion directly converted from ion flux.

Maximum flux of the neutral particles to the first mirror were calculated from multiplication of the maximum normalized flux 3.6 x 10^{-5} (Figure 5) by the input neutral particle flux values of previous paragraphs as seen in the table 4.

Maximum neutral particle flux (/m^2·s) on the first mirror of ITER divertor VUV	PFPO-1 W divertor	FPO W divertor
Attached	7.54 x10^{14}	3.32 x 10^{13}
Detached	1.22 x10^{14}	4.82 x 10^{13}

Table 4 The maximum neutral particle flux to the first mirror from the impinging neutral particle flux to DFW in new SOLPS-ITER calculation (#9 procedure). These flux values are derived from multiplication of maximum normalized flux 3.6 x 10^{-5} (Figure 5) to the flux numbers on DFW from IMAS database.

The sputtering yield of SiC is 0.09 (already considering 15 deg. grazing angle) that was calculated by TRIM code. From this sputtering yield and the table 4, the sputtering rate is calculated in the table 5 by assuming that the total operation time of 1.2×10^7 seconds (= 400 s x 30000 pulses) corresponds to 10 years operation.

Maximum erosion rate (nm/year)	PFPO-1 W divertor	FPO W divertor
Attached	0.853	0.139
Detached	0.038	0.054

Table 5 The maximum erosion rate of the first mirror of ITER divertor VUV by impinging neutral particle flux to DFW from new SOLPS-ITER calculation (#9 procedure). These erosion rates are derived from the sputtering yield 0.09 of SiC (with 15 deg. grazing angle) for the neutral particle flux values of the table 4.

The other dominant source of neutral particles to the first mirror is the neutral particles directly converted from ions after the first collision on the wall surfaces. This portion of the neutral particles are not considered in the table 4 and 5. Note that the calculation by V. Kotov of the table 1 includes both portions of neutral particles. From SOLPS-ITER calculation, the ion fluxes to the first wall are derived as one of outputs, and these ion flux values can be treated as the source of neutral particles. The maximum ion flux numbers could be calculated for the various simulation cases of Be or W deposits on top of divertor (e.g. W *div.* case) for PFPO-1 and FPO W divertor cases from SOLPS-ITER [9]. From the database of calculation results, the case showing maximum flux number among these simulation cases is found to be the Be *top* FPO case with 3.75×10^{19} #/m^{2}s, while we assess W *div.* case with 5.27×10^{18} #/m^{2}s due to its higher ion temperature (~ 67 eV).

W *div.* cases were adopted as the representative cases in the current assessment because these W *div.* cases showed higher ion temperature compared to other cases. The maximum flux on the first mirror of ITER divertor VUV could be calculated by multiplication of maximum normalized flux 3.6×10^{-5} (Figure 5) by the maximum ion flux numbers on the diagnostic first wall (among various cases of Be or W deposits on top and bottom) from SOLPS-ITER simulations as tabulated in the table 6.

Maximum Ion flux (/m^2·s)	PFPO-1 W divertor	FPO W divertor
Attached	2.62×10^{13}	3.00×10^{13}
Detached	1.23×10^{14}	1.90×10^{14}

Table 6 The maximum flux estimation to the first mirror from the other portion of neutral particles. This portion of neutral particles are converted ones from ions directly after first wall collision. These flux values of this table are derived by multiplication of maximum normalized flux 3.6×10^{-5} (Figure 5) to the maximum flux numbers on the diagnostic first wall.

The sputtering yield of SiC is 0.09 that was calculated by TRIM code. From this sputtering yield and the table 6, the sputtering rate is calculated in the table 7 by assuming the total operation time of 1.2 x 10^7 seconds (= 400 s x 30000 pulses) corresponds to 10 years operation.

Maximum erosion rate (nm/year)	PFPO-1 with divertor	FPO with divertor
Attached	0.031	0.034
Detached	0.139	0.214

Table 7 The maximum erosion rate of the first mirror of ITER divertor VUV by the neutral particles portion directly converted from ion flux (SOLPS-ITER). Multiplication of 10 to the erosion rate can result into total erosion quantity considering 10 years operation times. This erosion rate is derived from multiplication of the impinging flux values of the table 6 by the sputtering yield, 0.09 of SiC.

From these estimations for two different sources of neutral particles of the table 5 and 7, the maximum erosion rates of the first mirror of ITER divertor VUV is found to be 3 – 4 order lower than Kotov's estimation (table 3). If we sum the values of the table 5 and 7 and multiply by 10 years, the maximum total erosion quantity (adopting the values from the attached PFPO-1 case) is estimated to be around 9 nm (~ 8.53 + 0.31) conservatively.

4. Experimental Setup

The plasma erosion test was performed for the SiC mirror sample using the divertor plasma simulator device. [10] The divertor plasma simulator device was constructed using an AF-MPD (Applied-Field Magneto-Plasma-Dynamic) thruster in the Korea Atomic Energy Research Institute (KAERI). This device can provide up to 10^{23} $m^{-2}s^{-1}$ H (or D) particle flux to the target. In this work, H (or D) particle flux of 5 x 10^{22} $m^{-2}s^{-1}$ was irradiated on the sample at the low gas pressure (~1 mTorr) with a plasma current, Ip = 80 A. To negatively bias the SiC mirror sample, the mirror sample was biased using metal holder, and this was electrically insulated from the support structure by the ceramic holder and exposed to the plasma through a 6 mm diameter hole. The biased voltage of the SiC sample (target) was fixed at 200 V as the impinging ion energy to the target. This ion energy was chosen considering the particle energy of 200 eV for charge exchange neutral particles of ITER in high density case of table 1. Due to the large particle flux, the temperature of the target area is increased to several hundred deg. C without active cooling on the target.

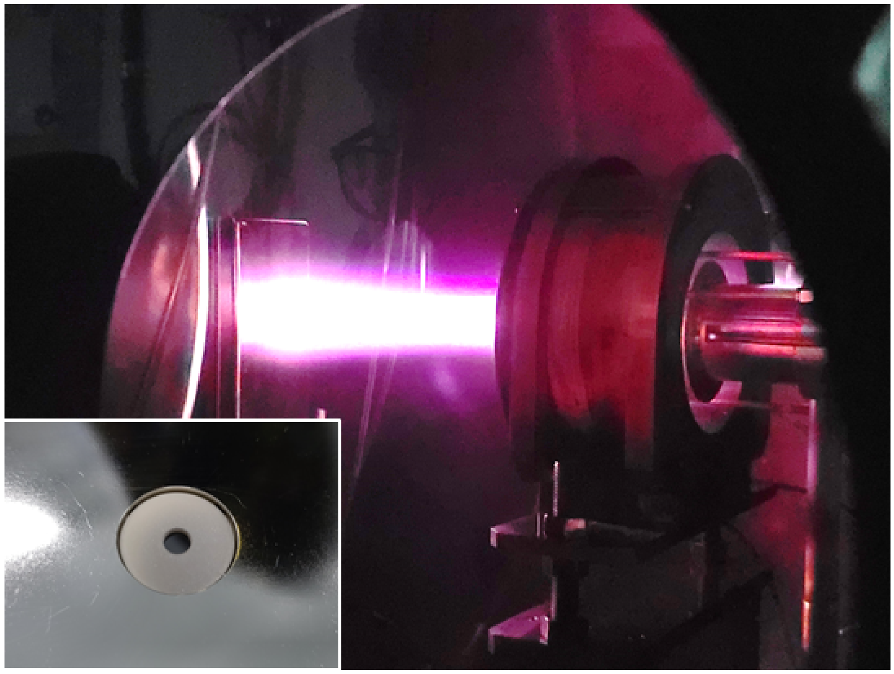


Figure 8 SiC mirror sample was exposed to H or D plasmas using the divertor plasma simulator

The measurements of surface topology and roughness were performed on sub-aperture stitching aspheric surface measuring machines (CCI-optics-RM, Taylor Hobson) in Korea Basic Science Institute (KBSI). In addition, SEM-EDS (ZEISS) photographs were taken to check the surface shape and chemical composition of the etched mirror.

5. Plasma erosion test result

In the preparation stage of the experiment, the target fluence of the ions was defined to be the same order of magnitude as the estimated neutral particle flux on the first mirror from Kotov's estimation (Sec. 3.2) conservatively. The target fluence of the ions is set to be larger than 6.4×10^{24} #/cm^2 which is EP case with the factor 2 (difference between atoms) of the table 1. The experiment was performed using this plasma irradiation device with the maximum duration ~ 200 seconds due to the device limit. Therefore the total experiment was performed in ~ 3 different plasma shots (~ 2 shots of H plasmas, 1 shot of D plasmas), and the surface morphology measurement was performed after each plasma discharge. The total irradiated fluence of H^+ ions was resulted to be 8.9×10^{24} #/cm^2 and that of D^+ was 1.9×10^{24} #/cm^2.

Figure 9 shows the total erosion depth due to this series of exposures of the SiC mirror sample to H and D plasmas. The total erosion depth was resulted to be 650 nm, and the depths for two H^+ and one D^+ cases were measured to be 275 nm and 375 nm, respectively. It is noted that the expected values of the erosion depth for these input fluences also can be calculated from the sputtering yield values in the table 2 for 90 deg. grazing angle case of hydrogen and deuterium atoms with 200 eV. From this calculation, the expected erosion depth is 937 nm for H^+ ions and 534 nm for D^+ ions, showing a relatively good agreement with the experimental results for D^+ case. The reason for the discrepancy between TRIM estimation and the experiment result of SiC erosion by H^+ ions is thought to be originated from that the sputtering yield of H^+ is energy sensitive in 100 eV ~ 200 eV region as seen in the table 2.

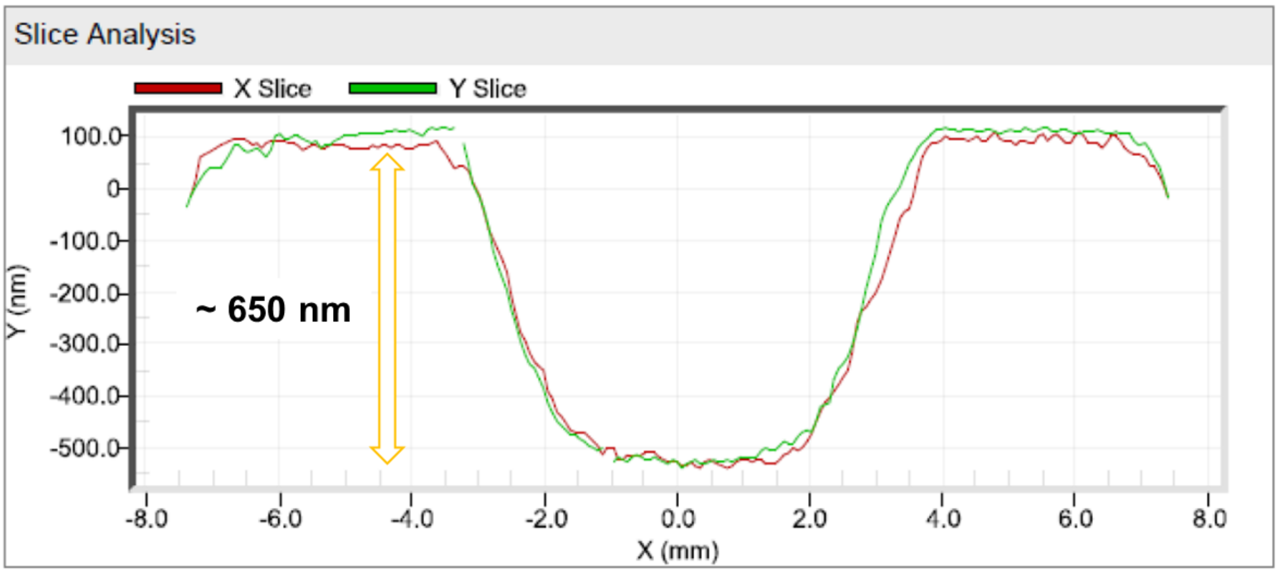


Figure 9 The erosion depth profile was measured after exposure to the plasmas of $8.9\text{x}10^{24}$ /cm^2 of H^+ and $1.9\text{x}10^{24}$ /cm^2 of D^+.

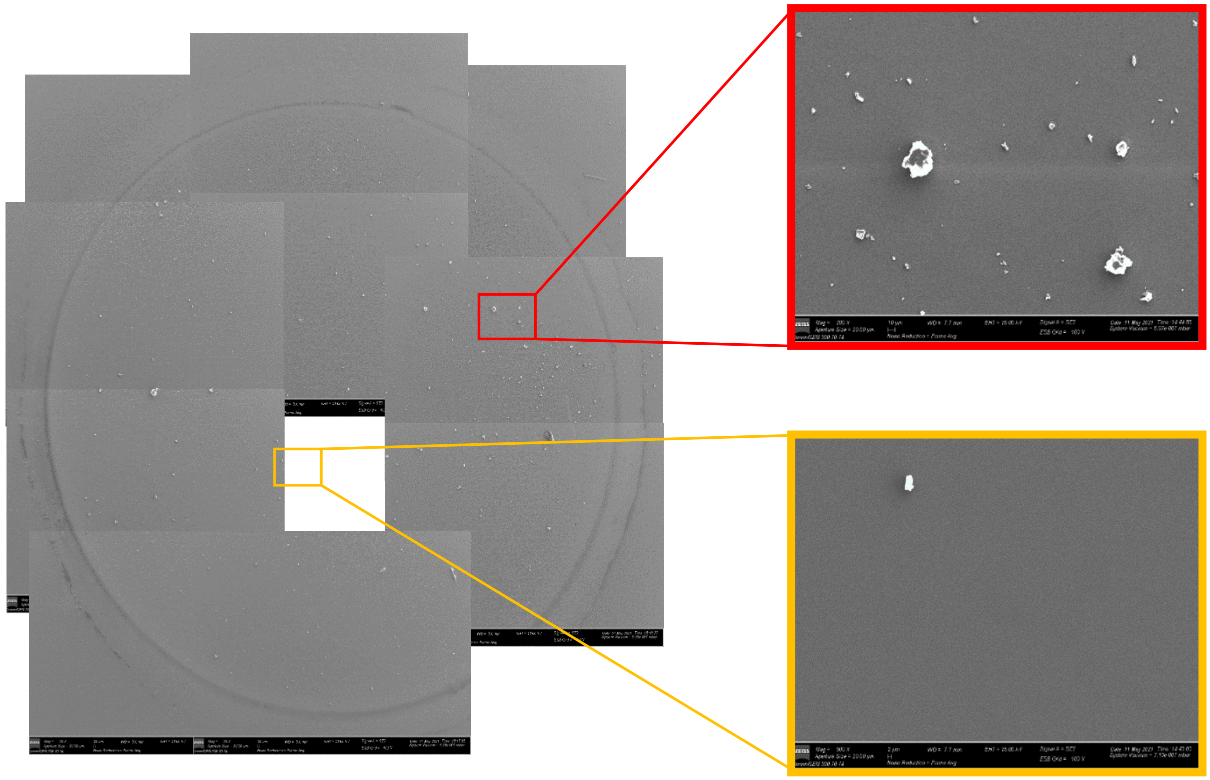


Figure 10 SEM images of the SiC mirror sample after exposure to the plasmas

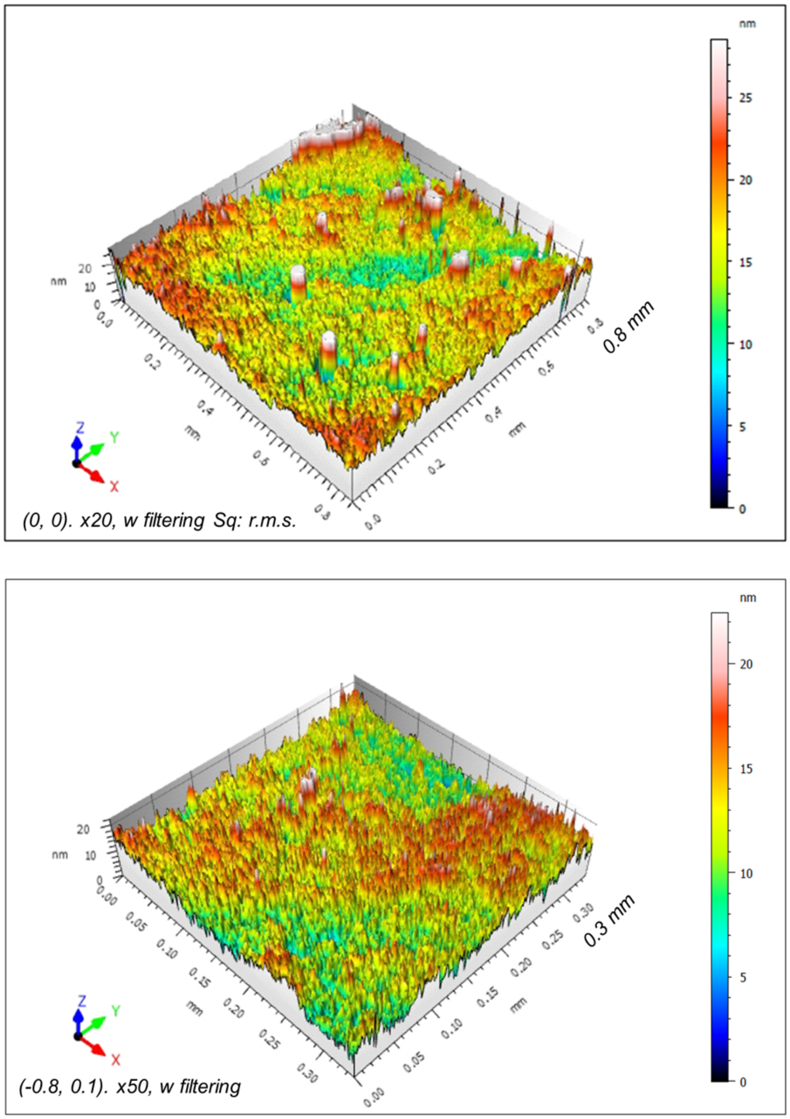
Figure 10 shows the SEM images of the SiC mirror sample after exposure to the plasmas. Particles with the size of several tens of micro-meters are dispersed on the mirror surface. EDS analysis showed that most of those particles are aluminum oxide that came off the insulation material of the mirror cover, and some of the particles are tungsten and copper that fell off the AF-MPD thruster electrodes (or anode and cathode). The surface except the dispersed particles was measured to be SiC.

The surface roughness values are derived by average of the measurement (r.m.s.) values for more than 5 different points on the mirror surface such as (±4, 0), (0, ±4), and several points near (0, 0), in mm units. The initial roughness of the mirror before the experiment is 2.6 nm. In the evaluation of the surface roughness, the abnormal measurement data such as dispersed particles from mirror cover and the round-shape pattern (in several hundreds nm) was filtered in the evaluation of the surface roughness (r.m.s.) as shown in Fig. 11.

The surface roughness was measured after each plasma discharge. The initial surface roughness of SiC mirror sample was 2.6 nm before plasma exposure. 2.7 nm was resulted after exposure of 8.9 x 10^{24} #/m^2 of H^+ (from two plasma discharge experiments), and 3.3 nm after exposure of 1.9 x 10^{24} #/m^2 of D^+. From this series of experiments, the gradual degradation of the mirror surface could be observed with total $\Delta \sim 0.7$ nm from the initial roughness value. Depending on the measurement location, this surface roughness value was varied. For example, 4.5 nm was found with magnification factor 20 in the point of (0 mm, 0mm) as the case of Fig. 11 a), while 2.9 nm could be derived with magnification factor 50 in the other point of (-0.8 mm, 0.1 mm) for the same mirror surface after the end of total experiments. It also needs to be noted that in the evaluation of the surface roughness, filtering was applied by cutting off the roughness data above the threshold value to delete the effect of discontinuous data such as dropped dust or round-shape pattern on the mirror surface.

	Total ion Fluence (ions/m^2)	**Erosion depth (nm)**	**Surface roughness (nm, r.m.s.)**
H+	8.9×10^{24}	275	2.7
D+	1.9×10^{24}	375	3.3

Table 8 The erosion depth and surface roughness after exposure to the plasmas. The surface roughness values in this table are the average of the measured roughness (r.m.s.) for more than five points on the mirror surface such as (0, 0), (±4, 0), (0, ±4) in mm units. The initial roughness of the mirror before the experiment is 2.6 nm. In the evaluation of the surface roughness, filtering was applied by cutting off the roughness data above the threshold value to delete the effect of discontinuous data such as dropped dust or round-shape pattern on the mirror surface. (Fig. 11)



a)

ISO 25178		
Height Parameters		
Sq	4.5107	nm
Ssk	-0.2616	
Sku	5.4930	
Sp	13.0200	nm
Sv	15.5400	nm
Sz	28.5600	nm
Sa	3.2394	nm

b)

ISO 25178		
Height Parameters		
Sq	2.9187	nm
Ssk	0.1180	
Sku	3.4948	
Sp	11.0200	nm
Sv	11.4300	nm
Sz	22.4500	nm
Sa	2.2959	nm

Sa: Arithmetical mean height
Sz: Maximum height
Sq: Root mean square height
Ssk: Skewness
Sku: Kurtosis
Sp: Maximum peak height
Sv: Maximum pit height

Figure 11 CCI topology images of the SiC mirror after the erosion test as examples of the measurement points. The measured surface roughness values (r.m.s.) of a) and b) after the end of experiments are 4.5 nm and 2.9 nm, respectively. The measurement coordinated from the mirror center and the amplification are described in the bottom of each figure. Dropped dust (several micrometers) or round-post-shape damage (in several hundred nm height) on the mirror surface was also identified, and these values were cut off (white part of image) in the evaluation of the surface roughness.

6. Conclusion

We performed the erosion test for the SiC first mirror sample based on the neutral particle flux estimation from the ZEMAX calculation. Estimation of neutral particles based on Kotov's SOLPS calculation in 2016 [8] and new SOLPS-ITER calculation in 2021 [9] is shown in table 9. Because Kotov's estimation is very conservative with assuming high plasma density in far SOL region such as near the wall, the recent calculation from ITER organization using SOLPS-ITER is considered to be more realistic.

		EP HD	**EP LD**
Neutral particle flux ($/m^2 \cdot s$) from Kotov's estimation		3.2×10^{17}	7.3×10^{16}
		PFPO-1 W divertor	FPO W divertor
Neutral particle flux ($/m^2 \cdot s$) from new SOLPS-ITER	Attached	7.54×10^{14}	3.32×10^{13}
	Detached	1.22×10^{14}	4.82×10^{13}
		PFPO-1 W divertor	FPO W divertor
Ion flux ($/m^2 \cdot s$) from new SOLPS-ITER	Attached	2.62×10^{13}	3.00×10^{13}
	Detached	1.23×10^{14}	1.90×10^{14}

Table 9 Summary of the neutral particle flux estimation on the first mirror of ITER divertor VUV. The Kotov's estimation (2016) with conservative assumption is two or three order of magnitude larger than the recent calculation of SOLPS-ITER (2021).

The plasma erosion test for the SiC mirror sample was performed in the divertor plasma simulator device. The target fluence of the ions during the experiment was 6.4×10^{24} #/cm^2. It should be noted that this flux values are two or three orders of magnitude larger than the neutral particle flux calculated by SOLPS-ITER of 2021. [9] If we consider that the calculated value of total erosion quantity is 9 nm for the first mirror of ITER divertor VUV for the recent input flux on DFW (the section 4.1.3), the mirror sample was extra exposed to two orders of magnitude larger fluence of ions (and plasmas) in the present experiment than the required value.

	Total Fluence (ions/m^2)	Erosion depth (nm)	Surface roughness (nm, r.m.s.)
H+	8.9 x 10^{24}	275	2.7
D+	1.9 x 10^{24}	375	3.3

Table 10 Summary of the erosion test results. Erosion depths are three orders higher than the estimated erosion depths of ~ 9 nm. (the tables 5 and 7) Note that initial roughness of the SiC mirror sample before plasma exposure is measured to be 2.6 nm (r.m.s.)

The result of table 10 shows the total roughness degradation (Δ ~ 0.7 nm) of SiC mirror sample after this sputtering experiment. The roughness degradation by this plasma sputtering is within the allowable range with regards to the reflectance dependence on the surface roughness for the VUV wavelength range.

In addition, we need to consider that the dependence of the sputtering yield (or surface roughness change) on the impinging angle of neutral particles which can increase the erosion quantity, because during the experiment, only 90 deg. grazing angled ion flux is irradiated. In the reference of previous research on the dependence of the sputtering yield on the impinging angle of particles, the difference is less than one order of magnitude. [12] Furthermore, the sputtering yield of SiC 0.09 used in this paper is the value calculated from TRIM code with consideration of this impinging angle (15 deg. grazing) on the first mirror already. In the verification experiment, we have made the verification experiment for two orders of magnitude larger erosion quantity, therefore it is plausible to expect that the SiC mirror degradation by the angled particle influx is also to be within the allowable level. It should be noted that the current assessment including the calculation is focused on the erosion effect, therefore with regards to the more realistic assessment of the deposition effect, the experimental results of the deposition effect on the mirror samples from various tokamak devices need to be referred. [13-15]

ACKNOWLEDGMENTS

This work was supported by the Ministry of Science and ICT of Korea, through the ITER project contract (RS-2022-00154842) and the Nation Research Foundation of Korea (RS-2022-00155950). The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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